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Amplitude Equalization of 40 Gb/s RZ-DPSK Signals Using Saturation of Four-Wave Mixing in a Highly Nonlinear Fiber

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Abstract *We report the first experimental demonstration of amplitude equalization of 40 Gb/s RZ-DPSK signals using saturation of FWM in a HNLF. We show effective power penalty reduction after wavelength conversion of an amplitude distorted signal.*

Introduction

Return-to-zero differential phase shift-keying (RZ-DPSK) has been recently suggested as a promising way to achieve higher system capacity and extended system reach due to its various advantages compared with conventional on-off keying (OOK), for instance larger dispersion tolerance, better resilience to fiber nonlinearity, and higher spectral efficiency [1].

Amplitude fluctuations of RZ-DPSK signals induced by amplified spontaneous emission noise and the interaction between optical fiber nonlinearity and dispersion (such as e.g. intra-channel four wave mixing) might however degrade the quality of the received signal. Those amplitude fluctuations will moreover be converted into nonlinear phase noise that has been shown to be a major source of impairment for DPSK systems [1]. Consequently, all-optical amplitude regeneration of RZ-DPSK signals will be needed to achieve improved signal quality in ultra long-haul transmission systems.

An extra requirement compared to conventional OOK regeneration methods is that the process involved should not affect the phase of the signal, or could even provide phase regeneration [2]. So far, only a few regenerative mechanisms suitable for RZ-DPSK signals have been proposed [2-3] and demonstrated [4-5]. Optical amplitude equalization using four-wave mixing (FWM) in an optical fiber has been reported for OOK signals [6]. FWM is a phase and intensity modulation preserving process that has already been used for wavelength conversion of DPSK signals [7], and whose amplitude regeneration capabilities for RZ-DPSK signals have been numerically investigated [8], but not demonstrated yet.

In this paper, we present the first experimental demonstration of amplitude equalization of 40 Gb/s RZ-DPSK signals using saturation of FWM in a highly nonlinear fiber (HNLF).

Experimental setup

The equalization scheme relies on saturation of FWM between the degraded RZ-DPSK signal and an RZ pulse train with identical duty cycle. A schematic of the setup used in this experiment is shown in Fig. 1. In our demonstration, we generate two identical RZ pulse trains by simultaneously modulating two continuous wave (CW) lasers at the pump and signal

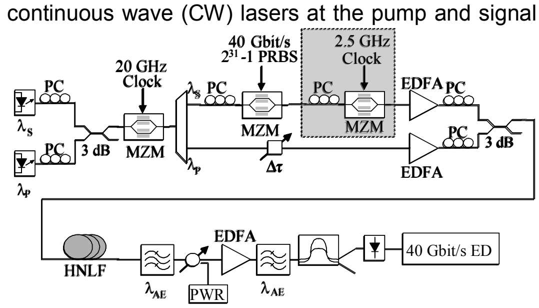

Fig. 1: Experimental setup. PC: polarization controller, PWR: optical power meter, ED: error detector.

wavelengths in a single Mach-Zehnder modulator (MZM) biased at a peak of its transfer function and driven with a 20 GHz clock signal. The two 40 GHz pulse trains with 33% duty cycle are then demultiplexed in an arrayed waveguide grating (AWG). The pulse train at the signal wavelength is phase modulated in the second MZM driven with a 40 Gb/s 2^{31}-1 pseudo-random bit sequence (PRBS), resulting in a 40 Gb/s RZ-DPSK signal. To intentionally introduce amplitude distortion to the RZ-DPSK signal, a third MZM driven with a 2.5 GHz clock signal is used in this experiment. The demultiplexed pulse train at the pump wavelength is then synchronized, amplified and combined with the amplified distorted RZ-DPSK signal before entering the HNLF. The polarization states of both signal and pump are optimized in order to ensure the best signal amplitude equalization. At the input of the HNLF, the signal and pump powers are 19 dBm and 22 dBm, respectively. At the HNLF output, the amplitude equalized FWM product is selected with an optical bandpass filter (OBPF). The signal is then detected in a single-ended pre-amplified receiver consisting of an erbium-doped fiber amplifier (EDFA), a tunable optical bandpass filter with a 3 dB bandwidth of 0.9 nm, a 1 bit delay interferometer for demodulation, and a 45 GHz photodiode. The fiber used in this experiment is a 500 m long HNLF. The nonlinear coefficient of the fiber is $\gamma = 10.6\ \mathrm{W^{-1}{\cdot}km^{-1}}$, and its zero dispersion wavelength is $\lambda_0 = 1553.6$ nm, with a dispersion slope of $S = 0.022$ ps/km/nm^2. The wavelengths of the RZ-DPSK signal, pump, and amplitude equalized FWM signal are $\lambda_S = 1560.60$ nm, $\lambda_P = 1555.84$ nm, and $\lambda_{AE} = 1550.91$ nm, respectively, in compliance with the ITU wavelength grid.

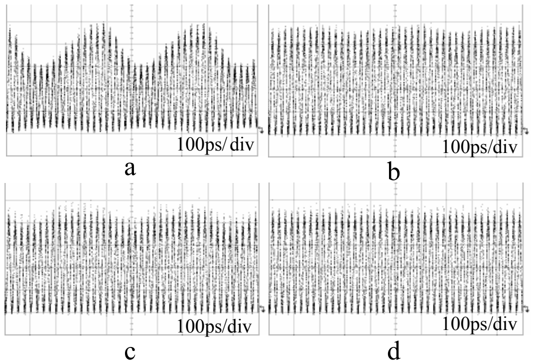

Fig. 2: Waveforms of the distorted signal when the MZM bias voltage is set to 6.0 V (a) and 8.5 V (c), and corresponding amplitude equalized signals, (b) and (d), respectively.

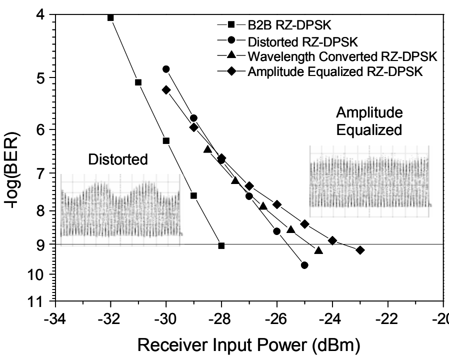

Fig. 3: Measured BER curves for back-to-back, distorted, wavelength converted, and amplitude equalized RZ-DPSK signals.

Results and discussion

Fig. 2 shows the waveforms of the distorted RZ-DPSK signals obtained with two different values of the bias applied to the third MZM, resulting in different levels of amplitude fluctuations, as well as the corresponding amplitude equalized signals. It can be seen that the amplitude fluctuation is significantly reduced in both cases.

Bit-error rate (BER) measurements results for the back-to-back (B2B), distorted, and amplitude equalized RZ-DPSK signals are shown in Fig. 3 for a MZM bias of 6.4 V. For comparison, the BER curve obtained after wavelength conversion of an RZ-DPSK signal without amplitude distortion is also presented in the figure. Waveforms of the distorted and equalized signals are also shown as insets in Fig. 3. Amplitude distortion induces a power penalty (at a BER of 10^{-9}) of 2.5 dB on the RZ-DPSK signal. This penalty is reduced to 1 dB after equalization (comparing the equalized signal to the wavelength converted RZ-DPSK signal without amplitude distortion). This penalty is attributed to the residual amplitude distortion observed in the equalized signal.

To further assess the amplitude equalization, the bias

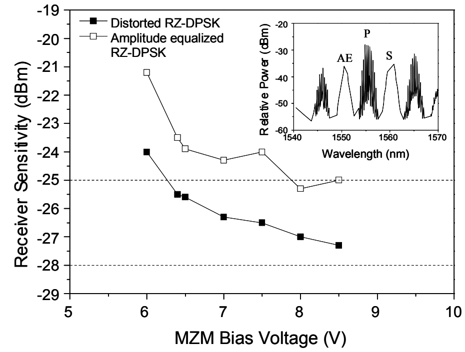

Fig. 4: Receiver sensitivity of the distorted and amplitude equalized RZ-DPSK signal as a function of the third MZM bias voltage. The inset shows the spectrum measured at the output of the HNLF when the bias voltage is set to 6.4 V (Resolution bandwidth 0.1 nm). P: pump, S: distorted RZ-DPSK signal, AE: amplitude equalized RZ-DPSK signal.

voltage of the third MZM is changed from 6 to 8.5 V to achieve decreasing modulation indices for the distortion of the RZ-DPSK signal. The receiver sensitivities for the distorted and equalized signals are shown in Fig. 4. It can be seen that, within the limited accuracy of the BER measurements, the receiver sensitivity of the distorted signal is limited by the back-to-back sensitivity of -28 dBm, while the sensitivity of the equalized signal is limited by that of the wavelength converted RZ-DPSK signal equal to -25 dBm. The inset shows the spectrum measured at the HNLF output, where the pump, distorted signal (MZM bias equal to 6.4 V), amplitude equalized signal, and other FWM products can be clearly seen.

Conclusion

Using a 500 m long HNLF, we have experimentally investigated amplitude equalization of 40 Gb/s RZ-DPSK signals using saturation of FWM. We have demonstrated that amplitude distortion can be efficiently suppressed and that the penalty between a distorted and undistorted RZ-DPSK signal can be reduced after wavelength conversion owing to the pump-saturation induced regenerative nature of the wavelength conversion process.

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